Cost-Effective Capacity Increase of Deployed Optical Networks to Support the Future Internet: the Multi-Band Approach

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Rasoul Sadeghi*, Bruno Correia*, Emanuele Virgillito*, Antonio Napoli†, Nelson Costa‡,
João Pedro‡§ and Vittorio Curri*
* Department of Electronics and Telecommunications (DET)
Politecnico di Torino, Corso Duca degli Abruzzi, Torino, Italy
Email: {rasoul.sadeghi, bruno.dearaujo, emanuele.virgillito, vittorio.curri}@polito.it
† Infinera, UK
Email: ANapoli@infinera.com
‡ Infinera Unipessoal Lda, Rua da Garagem 1, 2790-078 Carnaxide, Portugal
Email: {NCosta, JPedro}@infinera.com
§ Instituto de Telecomunicações, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal

***Abstract*—Band division multiplexing is proposed in this work as a cost-effective strategy to cope with the always increasing demand for capacity in optical networks. The potential of the proposed strategy is investigated considering two reference network topologies from Germany and the USA. We evaluate the impact of using C+L+S-band in terms of capacity and energy consumption. The use of signal regeneration to improve optical performance is also evaluated. We showed that, due to the worse Quality of Transmission (QoT) in the S-band, it provides the smallest capacity increase among the considered transmission bands. Nevertheless, placing some optical signal regenerators in this band enables increasing significantly its capacity. However, this enhancement of capacity is achieved at the cost of increased energy consumption (besides capital expenditures).**

***Index Terms*—Optical Networks, Optical fiber communication, Wide-band Optical network, transmission modeling, optical amplification**

I. Introduction

Network traffic keeps growing over time, pushed by the advances in technology, such as high definition video and 5G. Recently, the worldwide COVID-19 pandemic [1] was one additional factor contributing to this increase of required capacity. To cope with this demand for capacity and, simultaneously, limit the overall power consumption of telecommunication networks [2], the deployment of high capacity as well as power-efficient transceivers (TRXs) is desired.

Additionally, spatial division multiplexing (SDM) and/or band division multiplexing (BDM) [3] can be currently exploited by network operators to further increase the capacity of their Wavelength-Division Multiplexing (WDM) systems, which usually work in the C-band only, with a total bandwidth of around 4.8 THz.

BDM aims at exploits the full low-loss single-mode bands of optical fibers, namely of the widely deployed ITU-T G.652.D fiber, which exceeds 50 THz [4]–[7], for data transmission. This is a very cost-effective strategy to increase network capacity [4] since it uses the already existing optical fiber infrastructure, therefore providing some savings on the capital expenditure (CAPEX). In the [6], the effect of uniform and nonuniform traffic distribution effect on the network behavior in the BDM and SDM case in the C+L band in a transparent network by applying the Shannon capacity of LPs has been demonstrated. Moreover, ref [7] extended in the working bands and number of fibers in the BDM and SDM upgrades, respectively. It has been approved that BDM upgrade has an almost same behavior in the SDM upgrade, which is more cost effective upgrade. It is worth mentioning that, the both of above mentioned studies were in a fully transparent design and the BDM and SDM upgrades compared.

On the other hand, the SDM upgrade relies on the use of multiple fibers to transmit data. Therefore, this upgrade strategy depends on the availability of dark fibers or on the deployment of new ones.

Using signal regeneration is another strategy that potentially increases the network capacity by enabling higher capacity modulation formats. This approach corresponds to a a translucent optical network design, where the optical signal is regenerated at selected nodes of the network before the signal quality degrades below a threshold. The optical power optimization in translucent optical networks has been investigated in [8], by extending the generalized multiprotocol label switching (GMPLS) to support optical regeneration.

The power consumption of optical networks scales with their capacity and, therefore, minimizing it is critical. Some investigations have already been carried out focusing on the power consumption of TRXs. In [9], the authors showed that CMOS node size is decreasing every two years in the scaling of Intel's integrated circuit. In [10], the authors showed that the CMOS energy consumption depends on the node size, with an energy reduction of $\sim$30% in each process step. Additionally, the availability of digital signal processing application-specific integrated circuit (DSP ASIC)s at the respective CMOS node size has been shown in several other works [11]–[13].

The Optical Internetworking Forum (OIF) is also actively pursuing efficient TRXs implementations. As an example, it defined an implementation agreement (IA) for the application of coherent techniques in pluggable form factors in the year 2013 [14]. Additionally, one of its latest IAs defines the 400ZR, which is a power-efficient and cost-effective coherent interface to support 400 Gbps using the symbol rate of 59.84 Gbaud.

In this work, we investigate the potential of BDM for the upgrade of optical networks, focusing on the enabling of the L- and S-bands in addition to the C-band. Each band has a different Quality of Transmission (QoT), with the S-band showing the worse performance. Thus, improving the QoT in this band has the potential to provide the highest capacity increase. Therefore, this work also evaluates the use of signal regeneration on S-band, which impacts not only the network capacity but also the CAPEX and power consumption.

This paper is organized as follows. In section II, the methodology used to evaluate the QoT for a single span is explained. Section III depicts the considered network scenarios and assumptions followed in this work. The main results are presented and discussed in section IV, and, at the end of the paper, the main conclusions are outlined in section V.

II. Methodology

The accurate modelling of the signal propagation along an optical fiber requires taking into account the frequency dependence of the fiber parameters such as (1) attenuation, (2) chromatic dispersion and (3) nonlinear coefficients, particularly when BDM is considered. As an example, both (1) and (2) dependence on the frequency are shown in Fig. 1 for a standard single-mode fiber (SSMF). It can be noticed that, for the C- and L-bands, the attenuation coefficient is usually smaller than 0.2 dB/km while, on S-band, it may reach about 0.22 dB/km (for the higher frequencies). Additionally, the stimulated Raman scattering (SRS), a nonlinear effect that causes a power transfer from higher to lower frequencies [6] and that could be mostly ignored in C-band only systems, can no longer be neglected in the case of BDM due to the much wider transmission bandwidth. Thus, the optical power in S-band will not only be more attenuated due to the aforementioned higher loss, as depicted in Fig. 1, but the SRS will also cause the power depletion along the optical fiber propagation, causing this band to be the one showing the worse QoT when compared to the C and L-bands.

Another relevant aspect in MBT is that the optical signal amplification, made at the end of each fiber span, is performed for each band individually, as illustrated in Fig. 2. This approach enables having simpler and more efficient optical amplifiers since it lessens the amplifier requirements: they do not need to have a too broad bandwidth nor a too high output power

The software defined network (SDN) controller is also highlighted in Fig. 2. This element is quite important in BDM

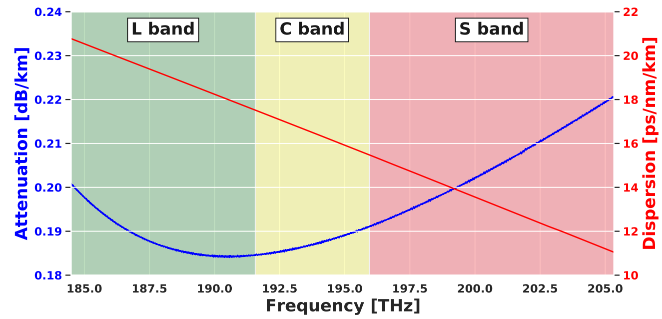


Fig. 1: Dependence of optical fiber attenuation and dispersion coefficients on frequency for a typical standard single-mode fiber (SSMF).

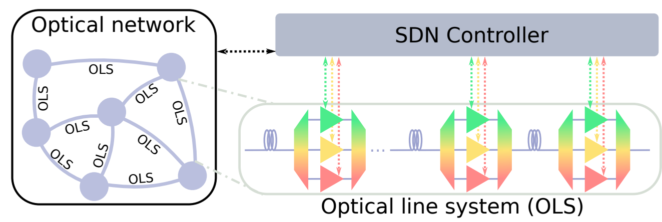


Fig. 2: Illustration of an multi-band OLS amplification.

systems since it is responsible for setting the working point of each amplifier which needs to consider the signal degradation of each band per span and amplifier characteristics. So, in order to counteract the smaller signal power in the S-band due to the higher loss and the SRS, the SDN controller needs to set higher gain in the S-band amplifiers, resulting also in the generation of additional amplified spontaneous emission (ASE) noise. Moreover, since the optical amplifiers for the S-band are still not fully mature, they usually show higher noise noise figure profiles than the C-band counterparts. It is the combination of all these effects that cause the aforementioned higher degradation of the QoT for this particular spectral band, compared with C+L-band systems.

One strategy to improve the QoT in S-band systems consists of deploying signal regenerators on selected intermediate nodes, instead of following a completely transparent approach. This approach will increase the implementation cost (CAPEX) and also power consumption, but presents the advantage of enabling a much higher capacity in S-band. In this case, similar capacity can be delivered in all bands which creates a more homogeneous network and, consequently, all connection requests can be allocated in any free channel(s), independently of the spectral band used.

In this work, each lightpath (LP) is modeled based on two Gaussian disturbances: ASE noise and nonlinear interference (NLI), introduced by the amplifiers and fiber propagation, respectively. To this end, the QoT at the end of each fiber span can be estimated by the generalized signal-to-noise ratio (GSNR) [5]:

$$\mathrm{GSNR}_i = \frac{P_{S,i}}{P_{\mathrm{ASE},i} + P_{\mathrm{NLI},i}} = \left(\mathrm{OSNR}_i^{-1} + \mathrm{SNR}_{\mathrm{NL},i}^{-1}\right)^{-1} \quad (1)$$

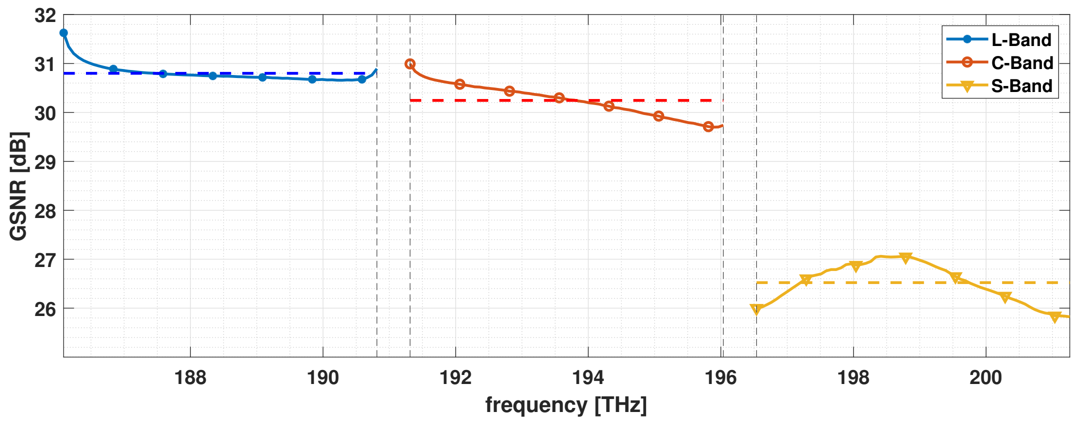


Fig. 3: GSNR profile for a single span of 70 km for L-, C-, and S-bands.

wehre $P_{S,i}$ is the fiber input power, and OSNR_i and $\text{SNR}_{\text{NL},i}$ are the optical signal-to-noise ratio and nonlinear signal-to-noise ratio, respectively, all evaluated for the i-th channel under test. The ASE noise power ($P_{\text{ASE},i}$) can be calculated as:

$$P_{\text{ASE},i} = hf_i\text{NF}(f_i)G(f_i)B_{\text{ref}} \tag{2}$$

where h is the Planck's constant, B_{ref} is the reference bandwidth, and $G(f_i)$ and $\text{NF}(f_i)$ are the gain and noise figures of the amplifiers in f_i, respectively. The Generalized Gaussian Noise (GGN) model is used to calculate the NLI contribution of fiber transmission [15], [16] given by:

$$P_{\text{NLI},i} = G_{\text{NLI}}(f_i)B_{\text{ref}} \tag{3}$$

where $G_{\text{NLI}}(f_i)$ is the NLI power spectral density and considers the effects of spectral and spatial variations of fiber loss as well as the spontaneous Raman scattering (SRS)-induced [17] inter-channel power crosstalk. Finally, the total GSNR of a LP l in the i-th frequency channel is given by:

$$\text{GSNR}_{i,l} = \frac{1}{\sum_{s\in l}(\text{GSNR}_{i,s})^{-1}} \tag{4}$$

following a disaggregated abstraction of the physical layer [18], [19]. The QoT evaluation done in this work is calculated using the open source library GNPy [20].

Erbium-doped fiber amplifier (EDFA) lumped amplification is considered for both C- and L-bands [21]. For the S-band, the use of a bench top thulium-doped fiber amplifier (TDFA), characterized as reported in [22], is considered. The fiber losses are fully compensated at the end of the fiber span. Average noise figures of 4.25 dB, 4.68 dB and 6.50 dB are considered for the EDFAs in C-, L-, and S-band respectively. A 500 GHz guard band is imposed between C-, L- and S-bands (dashed vertical lines in the Fig. 3). The Locally Optimized Globally Optimized (LOGO) [17] approach is used for the optical launch power optimization.

As a reference, the GSNR profile for a single span after the transmission of 64 channels in each band, where each channel is allocated a 75 GHz frequency slot, along 70 km of ITU-T G.652D fiber, is depicted in Fig. 3. In this scenario, the LOGO approach estimated an optimum launch power per channel of -0.4 dBm, -0.2 dBm and 0.6 dBm for the C-, L- and S-bands, respectively. As a consequence, the average GSNR for the C-band is 30.2 dB, with a minimum GSNR of 29.7 dB and a maximum GSNR of 31 dB, and the average GSNR for the L-band is 30.8 dB, with the minimum and maximum values of 30.6 dB and 31.6 dB, respectively. In the S-band, the average GSNR is 26.5 dB, showing values ranging between 25.8 dB and 27.1 dB. These results highlight that, as expected, the QoT in S-band is worse than the remaining ones. In this particular case, the GSNR value in the S-band is about 4 dB worse than in the remaining bands.

Table I depicts the TRX characteristics (bit rate, maximum allowed chromatic dispersion (CD), consumed power and required GSNR (RGSNR)) for the modulation formats considered in this work. The same RGSNR in back-to-back operation (B2B) for each modulation format as indicated in [23] is assumed.

The analysis of Table I shows that the use of higher modulation format leads to the increase of power consumption. However, the scaling of the power consumption is smaller than the one of the bit rate, indicating that it is more beneficial, not only from an CAPEX but also from an electrical power consumption point of view, to aim at using the more spectrally efficient modulation formats. Additionally, the higher the order of the modulation format, the lower the CD tolerance.

TABLE I: TRXs modelling assumptions.

TRX	mod. form.	Data rate [Gb/s]	CD tolerance [ps/nm]	P[W]	RGSNR [dB]
Flex	16QAM	400	20,000	20	21
	8QAM	300	40,000	18	18
	QPSK	200	50,000	16	14
	QPSK	100	100,000	13	11

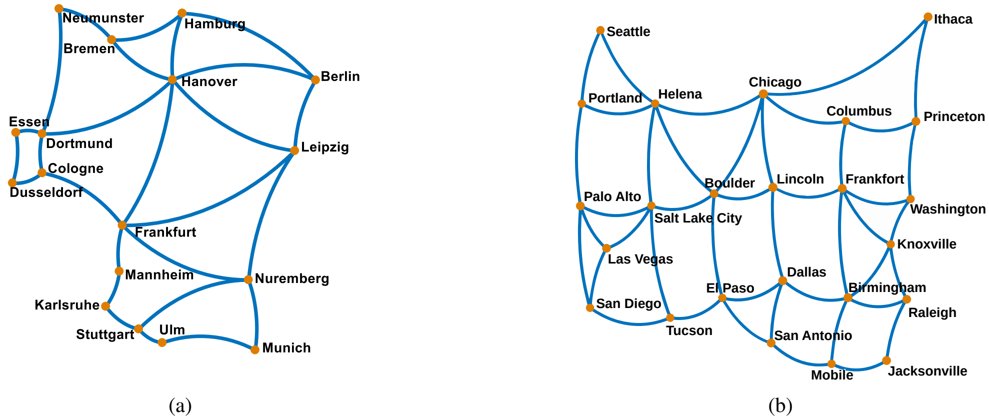


Fig. 4: (a) DT reference network's topology composed of 17 nodes with an average nodal degree of 3.1 and 26 links with an average link length of 207 km. (b) USNET reference network topology composed of 24 nodes with an average nodal degree of 3.6 and 44 links with an average link length of 308 km.

III. Network Scenarios and Regenerator Assignment Framework

Two reference networks with quite different characteristics are investigated in this work. These networks are depicted in Fig. 4 and consist in the German (DT), with a total of 17 nodes and an average link length of about 207 km, and USNET reference networks, with a total of 24 nodes and an average link length of about 308 km [22]. Span lengths of 70km are assumed for both networks.

In order for the control plane to route each LP, $N_{nodes} \times (N_{nodes} - 1) \times k_{max}$ paths are firstly pre-computed for each network by the k shortest path algorithm with $k_{max} = 5$, representing the possible routing space between all network nodes. Afterwards, and taking into account the QoT per channel, the control plane selects the modulation format that better fits the available GSNR, following the TRX characteristics presented in Table I.

Although operation at approximately 64 Gbaud only is assumed in this work, operation at smaller baud rate is also possible when using this TRX to increase reach, specially when it is limited by the TRX CD tolerance. An example of such case is shown in Table I for 100 Gbit/s QSPK, which operates at about 32 Gbaud.

As aforementioned, S-band presents the worse QoT, therefore resulting in a smaller offered capacity. Doing a selective deployment of optical signal regenerators in this band is a cost-effective strategy to increase its capacity as long as the number of deployed regenerators is kept reduced. In our approach, we select the solution that leads to at least the same capacity as a LP transmitted in the C-band, requiring the deployment of the minimum number of regenerator(s). To better illustrate the proposed strategy, Fig. 5 presents an example, retrieved from the DT network topology, where using regenerators is beneficial. In this case, a path between Hamburg (source) and Frankfurt (destination) with a total length of 630 km is depicted, containing two intermediate nodes (Leipzig and Hanover). The total path GSNR of the C-band is much higher than the S-band one for all frequencies, therefore resulting in a different offered capacity by the LPs in the C- and S-bands. In order to improve the QoT in S-band, first we test the deployment of a regenerator in Leipzig only. If that deployment does not allows achieving the same capacity as of a LP transmitted in C-band, we try to deploy a regenerator in Hanover only. Only if none of these solution work, we will deploy a regenerator in Leipzig and on Hanover.

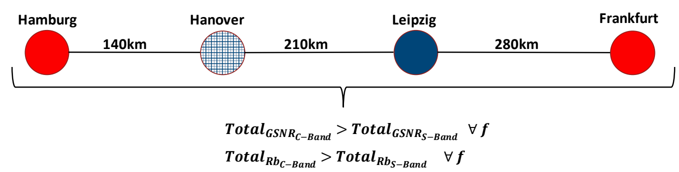


Fig. 5: Regenerator assignment description for the S-band

As a summary of the obtained results, the capacity, power consumption, and the number of deployed regenerator(s) for all LPs are computed and the average of these parameters (calculated per band), are reported.

IV. Results

This section presents the obtained capacity, the energy consumption, as well as number of consumed TRXs for the two reference networks in the three different bands with and without optical signal regeneration assignment in the S-band. Fig. 6 shows the total delivered capacity, in Tbps per band, the energy consumption, in kWatt, and number of used TRXs in the different bands for the DT topology, with (right bars) and without (left bars) regeneration in S-band. The analysis of Fig. 6a shows that the maximum capacity of the C- and L-bands are similar and of about 557 Tbps. However, the transparent capacity in S-band is about 12 Tbps smaller. This difference can be mostly eliminated by deploying a total of

TABLE II: Capacity, power consumption, and number of interfaces in the S-band and C+L+S-band for the DT and USNET topology with and without regenerator assignment.

			DT	USNET
Only S-Band	**Capacity[Tbps]**	**Without Regenerator**	545.1	520.0
		With Regenerator	557.0	591.8
	Power[kWatt]	**Without Regenerator**	27.0	42.4
		With Regenerator	29.4	51.9
	Device Count	**Without Regenerator**	272	552
		With Regenerator	336	623
C+L+S-Band	**Capacity[Tbps]**	**Without Regenerator**	1658.9	1648.0
		With Regenerator	1670.7	1720.0
	Power[kWatt]	**Without Regenerator**	81.4	128.5
		With Regenerator	83.8	138.0
	Device Count	**Without Regenerator**	816	1656
		With Regenerator	880	1727

64 extra TRX pairs (optical regenerators) in the intermediate nodes of some LPs. However, this increase in the number of deployed TRXs also impacts the power consumption, as depicted in Fig. 6b.

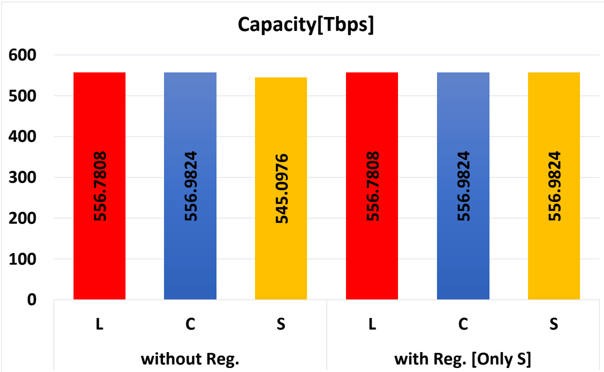
For this topology, the power consumption in a transparent network design is about 27 kWatts for all bands. With the deployment of optical regeneration, to achieve at least the same capacity in S-band as in C-band, the total power consumption increased by about 2.4 kWatts. The number of total point to point TRX numbers for DT topology depicted in Fig. 6c. It is observable that the average number of point to point TRX number for each link without regenerator assignment is 1 TRX per LP. However, in order to reach the same capacity level of C-band, it requires 336 TRXs in the S-band to reach the same capacity with C-band. In other words, S-and requires 64 more TRXs to work like C-band. For the particular case of DT network, the change in capacity, and consequently, in power consumption, is small when the deployment of optical regeneration is enabled. This effect is a consequence of the small average link length which enables using the same modulation format in all bands for most of the LPs.

Fig.7 shows the same results as Fig.6, but considering the USNET topology. In this case, and as depicted in Fig.7a, the capacity of C- and L- and S-band is about 579, 548 and 520 Tbps, respectively, thus leading to a capacity difference between the C- and S-bands of about 60 Tbps, which is a consequence of the longer average distance between links in USNET. On the other hand, By deploying some regenerators in S-band (71), the capacity of S-band is enlarged to 591 Tbps. We would like to highlight that the obtained capacity in S-band is substantially higher than the C-band one when optical regenerators are deployed. Since our criteria to deploy an optical regenerator in S-band is to achieve the same capacity as in C-band, this result may seem incorrect. However, that is not the case. Indeed, since we already have to deploy regenerators to guarantee that every LP in S-band has at least the same capacity as its C-band counterpart, we can explore the resulting higher QoT (provided by the optical regenerator) to try to deploy a higher capacity modulation format. The full exploitation of the higher QoT is the reason for the difference between the C- and S-band capacities. As an example, consider the LP from San Diego (source) to El Paso (target). In this case, the S-band can only support LPs operating at 100 Gbps while C-band can support 200 Gbps LPs. If an optical regenerator is assigned in the intermediate node (there is only a single intermediate node), the resulting GSNR of each of the new LPs enables the transmission of 300 Gbps using 8QAM modulation format, thus resulting in higher capacity in S-band than in C-band. Increasing the capacity in S-band came at the cost of deploying an additional 71 regenerators, which resulted also in the the energy consumption increase of 9.4 kWatts (from about 42.4 to 51.8 Kwatts).

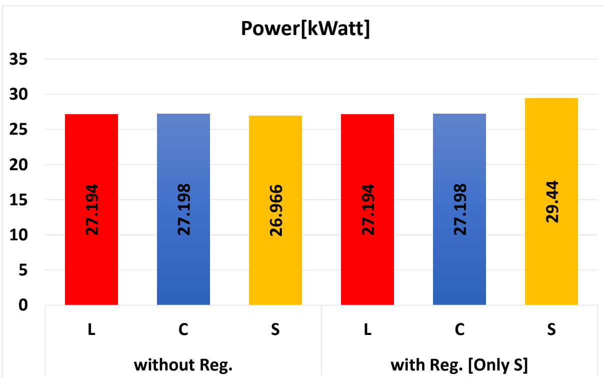
Table II presented to show the overall results of this work. According to this table, it is observable that for a network with small average link length the band capacities are close to each other and the consumed energy is lower. For instance, the capacity diference in the S-band with and without regenerator is about 12 Tbps. on the contrary in the USNET which is a large network in comparison to the DT network this difference is about 71 Tbps. Also, this behavior is observable in the power consumption in each band. The power consumption in the USNET is about $\times 2$ more than DT network topology. This table approves that the more average link length, the more difference between C and S-band.

V. Conclusions

BDM has been proposed in this work as a cost-effective strategy to increase the capacity of optical networks. Since optical performance is frequency-dependent, with frequencies in the S-band showing the worse optical performance, the use of optical signal regeneration in the S-band is proposed. However, this approach leads to an increase in CAPEX



(a)



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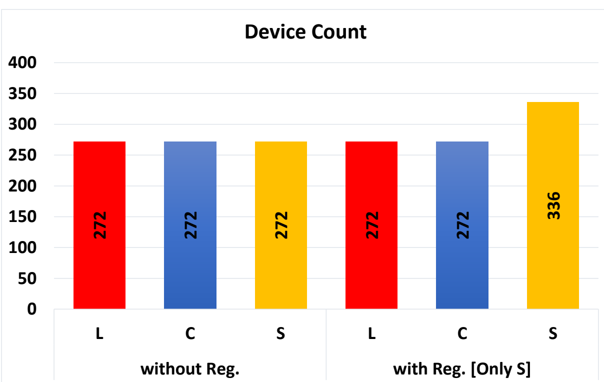
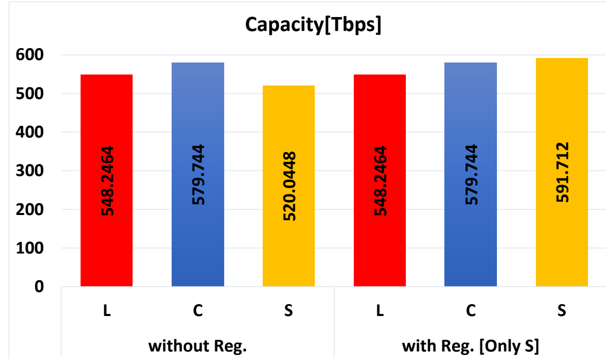


(c)

Fig. 6: (a) Capacity, (b) power consumption, and (c) number of point to point TRX in reference DT topology in a C+L+S-band system with and without optical regeneration in the S-band.



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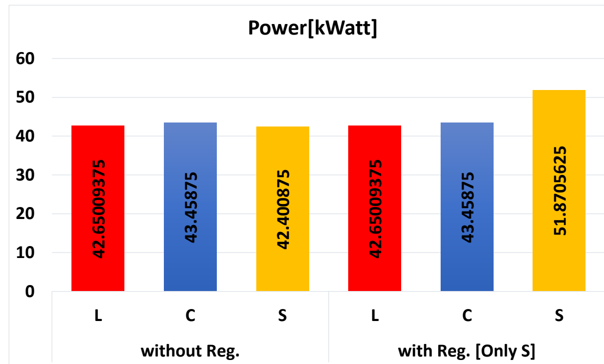

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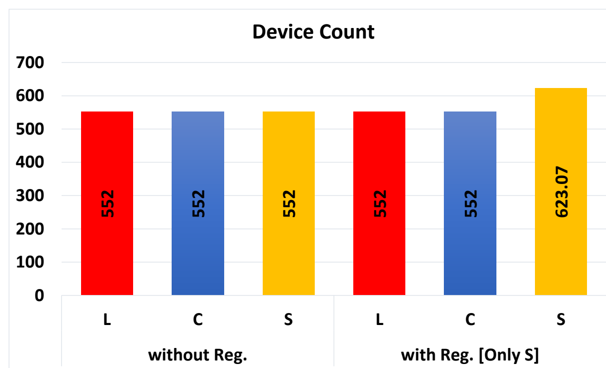

(c)

Fig. 7: (a) Capacity, (b) power consumption, and (c) number of point to point TRX in reference USNET topology in a C+L+S-band system with and without optical regeneration in the S-band.

and energy consumption. Therefore, we proposed to deploy optical signal regeneration only for the LPs showing worse performance in S-band than in C-band. This way, we get a more balanced network infrastructure, which simplifies the routing and wavelength assignment procedure and still keeps the number of deployed optical signal regenerators at a minimum. We showed that, for the smaller optical networks, the worse performance in S-band does not have a big impact on its maximum capacity. On the other hand, when longer LP are set, the LP capacity becomes more impaired by the optical fiber transmission effects, particularly in S-band. In this case, deploying optical signal regeneration may be critical to significantly increase the capacity in S-band

Acknowledgment

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